LINKING RIVER CHANNEL FORM AND PROCESS: TIME, SPACE AND CAUSALITY REVISITED

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ABSTRACT

Fluvial geomorphology has witnessed a continuing reduction in the time- and space-scales of research, with increasing emphasis on the dynamics of small site-specific river reaches. This shift can be regarded as part of a trend towards the understanding and explanation rather than description of how rivers change, which raises important questions regarding the relevance of such short time-scale and small space-scale research to understanding longer-term aspects of landform behaviour. The methodological challenges that arise from such intensive case study research are illustrated here using a detailed investigation of a river reach. Morphological changes within this reach are shown to be driven by: (i) catchment-scale processes associated with the interaction of discharge and sediment supply waves; and (ii) modification of these processes through morphological controls on erosion and deposition patterns and hence net channel change. The 'morphological conditioning' of channel response reflects the configurational aspects of channel change, and the importance of local characteristics in the understanding of system behaviour. Sensitivity to local conditions implies that short time-scale and small space-scale processes may be critical to channel behaviour, particularly if the system is interpreted in non-linear terms. Although it may be possible to identify statistically averaged stable states, non-linear system behaviour implies that system trajectories are sensitively dependent upon instantaneous system states. Thus, changes between average states can only be understood through an understanding of the sequence of configurational states through which the system evolves. © 1997 by John Wiley & Sons, Ltd.

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INTRODUCTION: A GEOMORPHOLOGICAL CONTEXT

Strahler (1952), in an attempt to distance geomorphology from the Davisian approach, argued for a dynamic basis for geomorphology grounded in fundamental scientific laws and combining: (i) the empirical, where field sampling or experimentation provides observations which can be subject to statistical analysis in an attempt to define cause and effect in an objective manner (pp. 935); and (ii) the rational, where '. . . *invention or intuition based upon the sum of* . . . *total experience, is used to formulate a mathematical model* . . .' (pp. 936). Strahler argued that as data accumulate and analysis proceeds, and with increased understanding, the empirical and the rational should unify upon reality. However, despite Strahler's argument that equal emphasis should be given to the empirical and the rational, the response in fluvial geomorphology (e.g. Dury, 1955; Leopold and Wolman, 1957, 1960; Schumm, 1960; Carlston, 1965; Kellerhals, 1967) was largely empirical, involving the statistical treatment of morphological parameters (e.g. width, depth, meander wavelength) and surrogates for their controlling variables (e.g. discharge). Often labelled the functional approach (e.g. Chorley, 1978), this gained support from the Schumm and Lichty (1965) functional typology of dependent, independent and irrelevant variables. This implied that at the reach scale, channel morphology would exhibit a long-term average or steady state that would be dependent upon surrogate variables for the dominant channel-forming processes (such as discharge, vegetation, sedimentology, etc.), and whose smaller time- and space-scale compo-

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nents (e.g. turbulent velocity fluctuations) would be largely irrelevant. Classic examples are the relationships between downstream variation in discharge and channel dimensions (the downstream hydraulic geometry of Leopold and Maddock (1953)), or the meander wavelength–channel width relationship (Leopold and Wolman, 1960). These are power laws in which the seductive quality of the trend may disguise order-of-magnitude local variability.

This approach is implicitly ergodic. Rather than setting out to establish how river channel processes resulted in specific changes in channel morphology, causes of channel change were inferred from the association between spatial variation in process and spatial variation in form. However, as Simpson (1963) argues, it is necessary to distinguish between 'immanent', ahistorical processes that may always occur (under the appropriate historical circumstances), and the 'configurational', the state or series of states which are the result of the interaction of the immanent with historical circumstances. The functional approach implicitly assumes that the immanent may be discovered from repeated observations of events or instances, requiring an assumption of exclusivity in which each immanent process maps directly onto a specific set of events. Simpson (1963, p. 29) argues that because events '. . . *are determined by the immanent characteristics of the universe acting on and within particular configurations* . . .', every event is unique. By implication, any statistical relationship will embody a set of events or instances each of which will have different configurational relationships, such that the resemblance between the statistical relationship and the immanent phenomenon remains unclear (and any empirical parameters may lack physical meaning). Furthermore, the ergodic assumption that is often central to a functional approach (e.g. Leopold and Maddock, 1953; Dury, 1955) is both invalid, in that it lacks rigorous dating control to justify the assumption (Paine, 1985), and subject to the critique that frequency of occurrence says little about *why* something happens (Sayer, 1984). Similarly, spatial co-variation of a particular aspect of channel morphology (e.g. width, depth, meander wavelength) with a surrogate process variable (e.g. discharge) says very little about what the relevant formative mechanisms might be. Indeed, generalizations based on such empirical relationships risk being the product of the sampling and experimental design rather than intrinsic to nature. A full explanation of events or instances can only be achieved through combining an evaluation of configurational properties with the appropriate immanent processes causing change (Simpson, 1963, p. 34); this is in essence a restatement of the 'covering law' model (e.g. Popper, 1972), but with a more critical stance about the scientific method used to reveal the covering law.

Research in fluvial geomorphology has begun to reflect this natural shift of emphasis towards 'full explanation', involving elucidation of how river channels change through time and space as they are subjected to temporal fluctuations in governing process variables (e.g. discharge, sediment supply from upstream). To establish the effects on a river reach of a change in discharge or sediment supply, it is necessary to observe what the channel does as discharge and sediment supply change. This requires intensive field study of sections of river channel small enough for practicable investigation, ideally combined with laboratory experimentation and numerical modelling. Fieldwork is an essential function, however, defining realistic configurational circumstances (boundary and initial conditions) within which to experiment or model. For practical reasons, fluvial geomorphologists have found advantage in continuing to collapse the time- and space-scales of enquiry, and in observing and attempting to measure what specific reaches of river channels do over short periods of time. Reduction of both time- and space-scales occurs in parallel for, as Church and Mark (1980) imply, processes that affect morphology over smaller space-scales often operate over shorter time-scales. Implicit in this trend is also a move away from mathematical generalizations based on surrogate or 'output' variables to a more detailed study of the physical mechanisms and system state variables associated with particular events.

The list of fluvial geomorphologist who have followed this trend is long (e.g. Carson and Lapointe, 1983; Dietrich and Smith, 1983, 1984; Ashworth and Ferguson, 1986; Best, 1986; Dietrich, 1987; Roy and Bergeron, 1990; Ashmore *et al*., 1992; Clifford and Richards, 1992; Laronne and Duncan, 1992; Warburton, 1992; Biron *et al*., 1993; Goff and Ashmore, 1994; Lane *et al*., 1995; Rhoads and Kenworthy, 1995), which perhaps indicates final recognition of Strahler's call for a truly *dynamic* geomorphology. However, this small-scale intensive study of river channels in particular environments raises important philosophical and methodological questions. For example, are they a field-based equivalent of laboratory experiments (cf. Ashworth and Ferguson, 1986), in which collapsing time- and space-scales allow one to understand the behaviour of larger-scale or less dynamic fluvial systems? As Kennedy (1990) and Baker and Twidale (1991) ask of geomorphology

more generally, we must assess the value of these *particular*, detailed, and time- and place-specific case studies in increasing our *general* geomorphological understanding. From a different perspective (Simpson, 1963), do we now know enough about the immanent, but not enough about the way in which configurational properties interact with immanent processes to produce events and instances? If the bounds of relevant immanent knowledge are finite, should geomorphologist now seek to understand and explain particular manifestations of specific processes in given places. If so, this provides a rationale for more case study research, but what does this mean for the ability to predict long-term landform evolution?

Faced with these questions, this paper aims to illustrate the implications of one particular case study for our understanding of the relationship between river channel form and process, and to raise some of the methodological issues associated with small-scale site-specific research. It does so by considering three related themes: (i) the nature of the link between channel form and process revealed by intensive study of a dynamic river system; (ii) the significance of the conditional role of channel morphology in this link; and (iii) the implications for the assumed dependence, independence and irrelevance of morphological variables with changes in spatial and temporal scale. The conditioning of process feedbacks by the channel morphology is shown to represent a sensitivity to initial conditions whose effects on channel evolution may be felt beyond the specific time- and space-scale under consideration.

The empirical evidence was obtained during the summer of 1992 from a braided reach of an actively changing river in the Swiss Alps. Located in a glacierized catchment, this had a strongly diurnal discharge regime and lacked vegetation. The bed material was heterogeneous, containing sand, gravel and cobbles. The methods used to gather the data have been largely detailed elsewhere, and in summary involved: discharge measurements obtained from depth-averaged gauging combined with a stage recorder and hydroelectric power station record (Lane *et al*., 1996); information on bedload sediment supply, obtained by deploying a Helley–Smith bedload sampler (Lane *et al*., 1995); and photogrammetric and tacheometric survey used to obtain accurate and dense digital terrain models (DTMs) of the study reach, closely spaced in time and space (Lane *et al*., 1994). The DTMs allowed visualization of channel morphology, and visualization and quantification of net and distributed volumes of channel change from intercomparison of consecutive DTMs.

LINKING RIVER CHANNEL FORM WITH PROCESS

A common problem faced by geomorphologist is identification of the dominant process responsible for creation of a particular form. When choosing between different, often equally plausible, process-based explanations, it is necessary either to reconstruct processes at the time of morphological change, or to observe processes as they happen. Only then is it possible to resolve controversies over, for instance, which process or event (e.g. discharge) is dominant (cf. Richards, 1982).

This problem is illustrated by the interaction of discharge and sediment supply fluctuations in causing channel change at the study site. Figure 1, based on subtraction of successive DTMs, presents the apparent effects of changes in discharge on net volumes of morphological change. The DTMs were based on surveys at the minimum and peak of the diurnal discharge hydrograph (on most occasions, at 10am and 5pm respectively), with additional DTMs being obtained on some rising limbs. The points on Figure 1 are of erosion and deposition volumes for periods when discharge was either only increasing (comparing a DTM at the hydrograph minimum with a DTM at the subsequent hydrograph peak) or only decreasing (comparing a DTM at the hydrograph peak with a DTM at the subsequent minimum). This illustrates a close correlation between the magnitude and direction of discharge change and the volume of erosion or deposition; with larger discharge increases, the volume of erosion is greater. However, closer inspection reveals a more complicated pattern, with points later on the rising limb tending to show less erosion, or even net deposition, and those on the falling limb showing deposition largely independent of the scale of discharge decrease, when sediment supply is probably the dominant influence (Lane *et al*., 1996). This observation emphasizes that discharge and sediment supply act together to control river channel change.

Sediment supply is determined both by patterns of erosion and deposition upstream, and by more local supply of sediment from eroding banks within the reach. Sediment supply from upstream reflects the interaction of daily discharge fluctuations with the availability of transportable sediment in the reach immediately

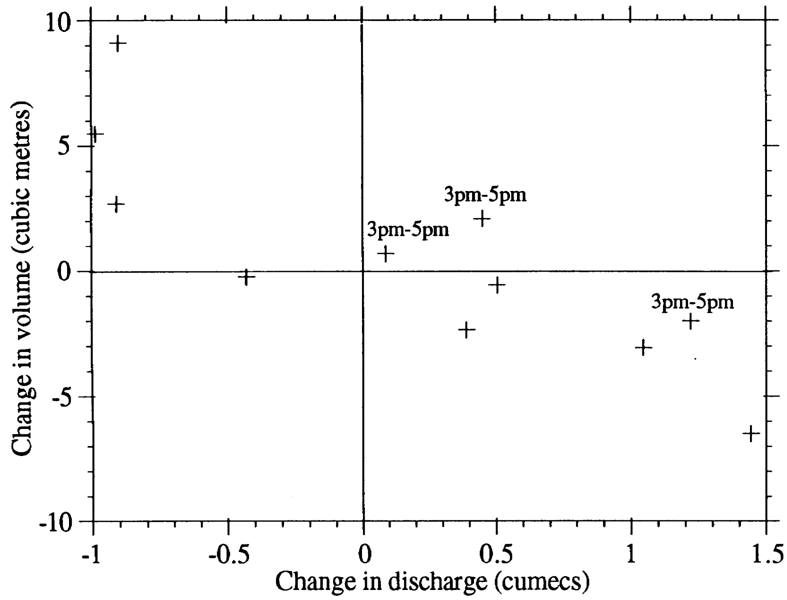

Figure 1. A plot of the volume of erosion (negative) or deposition (positive) versus the associated change in discharge, where the discharge change was either only increasing or only decreasing during in the time periods between DTM acquisition.

upstream, in turn modified by the interaction of sediment supply, discharge and erosion and deposition patterns in that reach. It is thus impossible to define a particular discharge as being 'dominant', because of the multiple discharge and sediment supply combinations that could cause channel change. This conclusion is supported by what is known about sediment rating curves, which rarely show a simple functional relationship between discharge and sediment transport rate (e.g. Bathurst, 1987), because both bed sediment availability and upstream sediment supply affect at-a-point sediment transport rates.

The critique of the concept of a 'dominant' or formative event for a particular river reach may be developed by taking a more holistic view of the dynamics of a river with respect to its entire drainage basin. The dynamics of the Arolla river can be conceived in terms of interacting waves of discharge and sediment, moving at different velocities through the catchment. This interaction creates temporary zones of both sediment storage and sediment erosion, which in turn determine future patterns of storage and erosion. The behaviour observed in the study reach reflects its position in the catchment, and the local interaction of externally imposed discharge fluctuation with internally driven controls on sediment supply. Understanding the behaviour of the reach cannot be divorced from consideration of its position within the catchment. A similar observation has already been made of meandering systems. Furbish (1991) noted that within a meander train, each individual meander bend delivers to its downstream neighbour a distinct velocity distribution that reflects both the flow structure entering the bend and the bed topography within the bend. It may also influence its upstream neighbour through backwater effects. Thus, evolving meander bends are interdependent, and the migration of an individual bend can only be understood by reference to its position within the meander train. These observations justify a conclusion that to make complete sense of Figure 1, more system-scale data are required.

MORPHOLOGY AND FEEDBACK

An immediate implication of the above discussion is that the response of the system to an imposed process event depends on the 'conditioning' effect of previous events (Newson, 1980), which define the context that determines system response. This conditioning has a spatial manifestation, both because process patterns depend on a three-dimensional morphological initial condition and the spatial distribution of transportable sediment, and because of the time taken for the effects of a particular event to be propagated through the system.

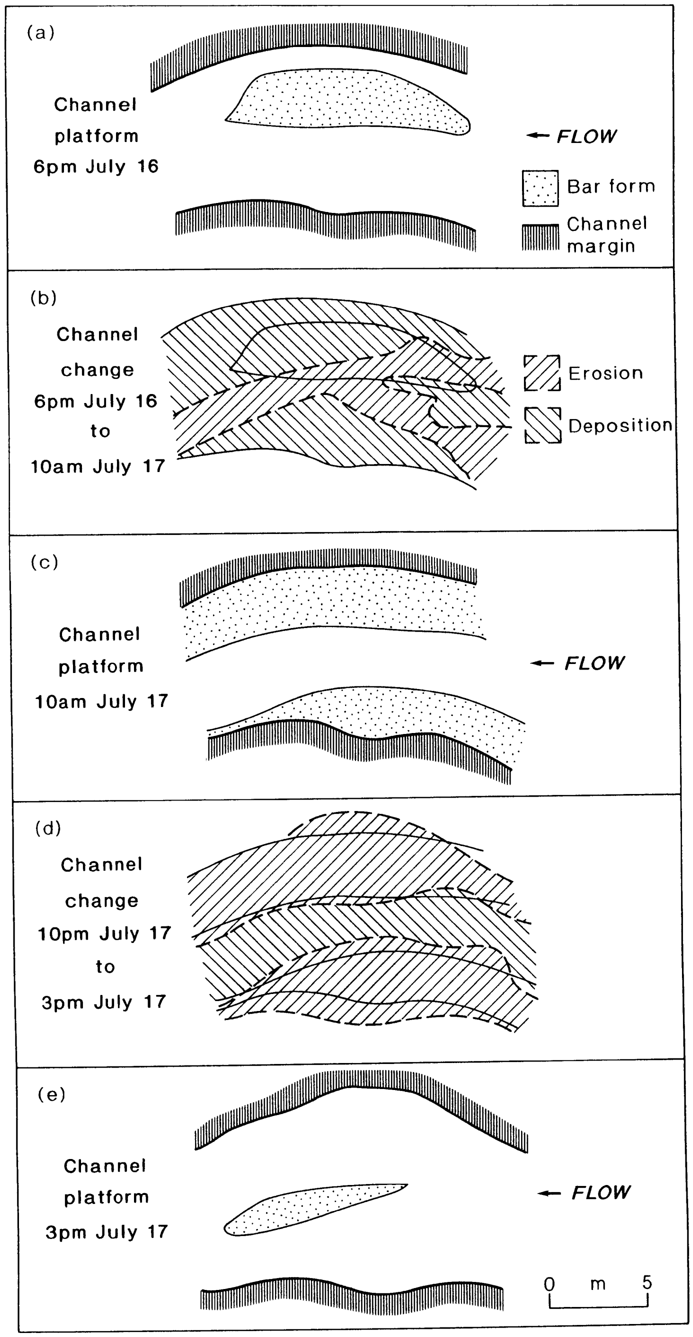

Figure 2. Contour plots of a surface of difference for a subreach of the study site, obtained by comparing a DTM acquired on the evening of 16 July (coincident with a discharge hydrograph peak) with one obtained on the morning of 17 July (coincident with the following discharge hydrograph trough).

At the basin scale, the dependence of sediment transport rate, and by implication channel change, on channel configuration has been illustrated by Paola (1996), who treats a braided river as a stochastic system to develop spatially averaged equations for sediment flux through a procedure that is analogous to the Reynolds-averaging process in turbulence studies. Although the averaging process has to assume a length scale large enough that the

wetted area of channel does not change as a function of distance downstream, and so width changes are ignored, the resultant equations for sediment transport and width change are dependent upon both downstream variation in bed gradient and (corrected) drag coefficient terms. The latter do not include the effects of form drag (e.g. due to barforms), such that the effects of channel configuration are only partially represented, but the importance of channel morphology as a control on transport rates is apparent in this approach. Thus, as channel morphology evolves, so the channel's sediment transporting capacity evolves. At least some of the scatter on Figure 1 may therefore be explained by the effects of different channel morphologies upon the sediment transport process, in addition to the effects of sediment supply from upstream.

The importance of morphological control of sediment transport processes is reinforced by consideration at the within-reach scale. The net volumes of change plotted on Figure 1 are manifest as a spatially distributed pattern of both erosion and deposition within the study reach. Figure 2 shows a schema of a series of contour plots of erosion and deposition patterns in the Arolla river reach (based on diagrams in Lane *et al*. 1996), obtained during a single 24 hour monitoring period. Overnight between 16 and 17 July, a general situation of net aggradation is reflected in deposition on both sides of the channel, but there was also some erosion, involving scour of a narrow channel through the middle of the reach (Figure 2b). By the morning of 17 July, there was a single channel flowing through this reach (Figure 2c). This morphology, in turn, determined the effects of the morning discharge rise, with the lateral deposits acting as a sediment source for new erosion (Figure 2d). Downstream deposition then encouraged the upstream growth of a new medial bar during this period (Figure 2e). These observations suggest that morphology, itself produced by the interaction of previously imposed discharge and sediment supply, determines the way in which current sediment supply and discharge fluctuations interact to cause particular patterns of morphological change. A strong coupling between form and process is manifest as a spatially distributed feedback (e.g. Ashworth and Ferguson, 1986).

In dynamic river channels, such a feedback implies a state of continual change which minimizes the value of a conceptual framework focusing on adjustment of channel form to a prevailing process regime. This continual change results from continually changing imposed process events (discharge, sediment supply) operating in the context of an existing channel morphology and sedimentology (Lane *et al*. 1996). As the process events cause changes in morphology and sedimentology, so those changes result in a different response to similar process events. The channel can thus be envisaged as being on a kind of trajectory, where what goes on in the future is critically dependent upon what happens in the present, what went on in the past, and what is taking place in reaches upstream and downstream of the reach in question. To seek to explain channel change without reference to both these time and place circumstances is inadequate; a river's evolutionary behaviour is 'understood' by combining evidence of particular imposed *external* conditions (such as discharge or sediment supply events associated with upstream contributing areas of both water and sediment) at particular points in space and time, with *internal*, primarily topographical and sedimentological, information. As Schumm (1991) argues, the history of a system matters.

This suggests that all river channels will behave differently, at least in terms of their *appearance*. Our knowledge of *how* river channels change depends on which rivers we study, where and when. This means that generalization is based not on functional correlations of 'output' properties (of both form and process) but through understanding the physical interdependence of 'internal' distributions of form and process. As erosion and deposition patterns are spatially distributed through the effects of channel morphology, and because net volume is the spatially-integrated effect of these patterns, it follows that channel morphologies will have an important effect upon the ability of a reach to move sediment. Internal distributions of erosion and deposition, as determined by channel morphology, account for the dependence of sediment transport rates on channel configuration.

TIME, SPACE AND CAUSALITY

These observations have implications for the ideas of Schumm and Lichty (1965) regarding the dependence, independence or irrelevance of form and process variables in empirical functional relationships between form and process variables. For example, it is assumed that an average morphological variable (e.g. channel width or meander wavelength) is dependent on a catchment-representative, independent process variable (e.g. bankfull

discharge). Examples of such an assumption include Kellerhals (1967), Schumm (1968) and Ackers and Charlton (1970). Schumm and Lichty (1965) argued that as the time- and space-scales of enquiry reduce, one begins to focus upon fluctuations around a particular state, in which form and process continually switch between being independent and being dependent. The form–process feedback described above, set within such a framework, is simply a matter of changing time- and space-scales, with the significance of form and process and the status of variables being determined by the scale which is chosen.

These fundamental tenets of time, space and causality have gained much credence (e.g. Sugden and Hamilton, 1971; Jackson, 1975). As de Boer (1992, p. 315) argues, '*systems at very much lower hierarchical levels fluctuate too rapidly to affect the level of interest . . . these exist both upper and lower limits for scales relevant to explaining system behaviour* . . .'. Church and Mark (1980) note that for situations where a process has a characteristic time-scale which is much shorter than the time-scale of interest, it may be 'relaxed', but not ignored. When processes that are effective over longer time-scales and larger space-scales are dominant, the detail of high-frequency process variation at shorter time-scales and smaller space-scales is either irrelevant (e.g. Jackson, 1975) or at least capable of incorporation by simple parameterization using an average term (e.g. Church and Mark, 1980). In such situations, the variables may be 'relaxed'.

However, there are limits to this interpretation. Recognition of feedback within a system implies that it may not be possible to separate different time- and space-scales so conveniently, as events occurring at different time- and space-scales may have a net effect upon the system, and this is partly due to sensitivity to initial conditions. Morphological conditioning implies that the response of a system is not simply a reflection of imposed external processes, but also depends on the internal system state. This may, in turn, indicate the potential for non-linear behaviour (Lorenz, 1963), where there are critical periods in a system's behaviour where short-term, small-scale processes are magnified rather than damped, and result in long-term, large-scale system evolution.

The importance of shorter time-scales and smaller space-scale processes in controlling longer-term system behaviour can be illustrated by the temporal behaviour of the Arolla study reach. Figure 3 shows the 'age' of the river bed surface; this is defined by allowing a grid cell to accumulate longevity if there is no erosion or deposition in the time between consecutive DTMs. After 33 days, and using the terminology of Brunsden and Thornes (1979) and Huggett (1988), there seem to be both 'soft spots' of rapid change and 'stagnant areas' of little change. Relict elements of the main medial bar apparent at the beginning of the field season were maintained over this period (Figure 3). This bar may be envisaged as a 'fossil geomorphology', formed by the cumulative effects of meltwater processes in the preceding melt season (the summer of 1991). During the 33 day study period, the diurnal cycle of scour and fill, quasi-steady in a statistically averaged sense, resulted in processes operating around the bar such as sediment supply to the bar head and bank erosion. Thus, in the channel on the true right of the main medial bar, repeated formation and destruction of smaller medial bars was observed. This resulted in erosion of the main medial bar, so enlarging the channel. In turn, this altered the nature and form of the process of construction of the smaller bars, as the channel was no longer so confined, and the small bars could take on a more lobate form. Changes in the nature of bar formation resulted in different medial bar erosion rates. This example shows that susceptibility to change is responsible for spatial variation in age (Brunsden and Thornes, 1979), and also that this susceptibility is a consequence of morphology, which defines the spatial extent of process activity and hence morphological change. Longer time-scale and larger space-scale evolution of the main medial bar is controlled by the effects of shorter time-scale and smaller space-scale processes, which themselves are not fixed but evolve through feedback processes. By the end of the study period in the above example, a spatially distributed hierarchy of surface 'ages' is evident within the same system. As the long-term behaviour of the larger-scale bar is a product of events acting on a smaller time- and space-scales, and given that the system is sensitive to initial conditions (through morphological conditioning), this implies that particular short time-scale and small space-scale processes do have implications for longer time-scale and larger space-scale behaviour. Any attempt at scaling-up to longer-term landform evolution must recognize this.

Recent research has begun to suggest that fluvial systems may display non-linear (chaotic) behaviour. Phillips (1992) has undertaken qualitative stability analysis (Pucchia and Levins, 1985) of the mass continuity equation formulated for a fluvial system to show that all rivers have the potential to exhibit chaotic behaviour,

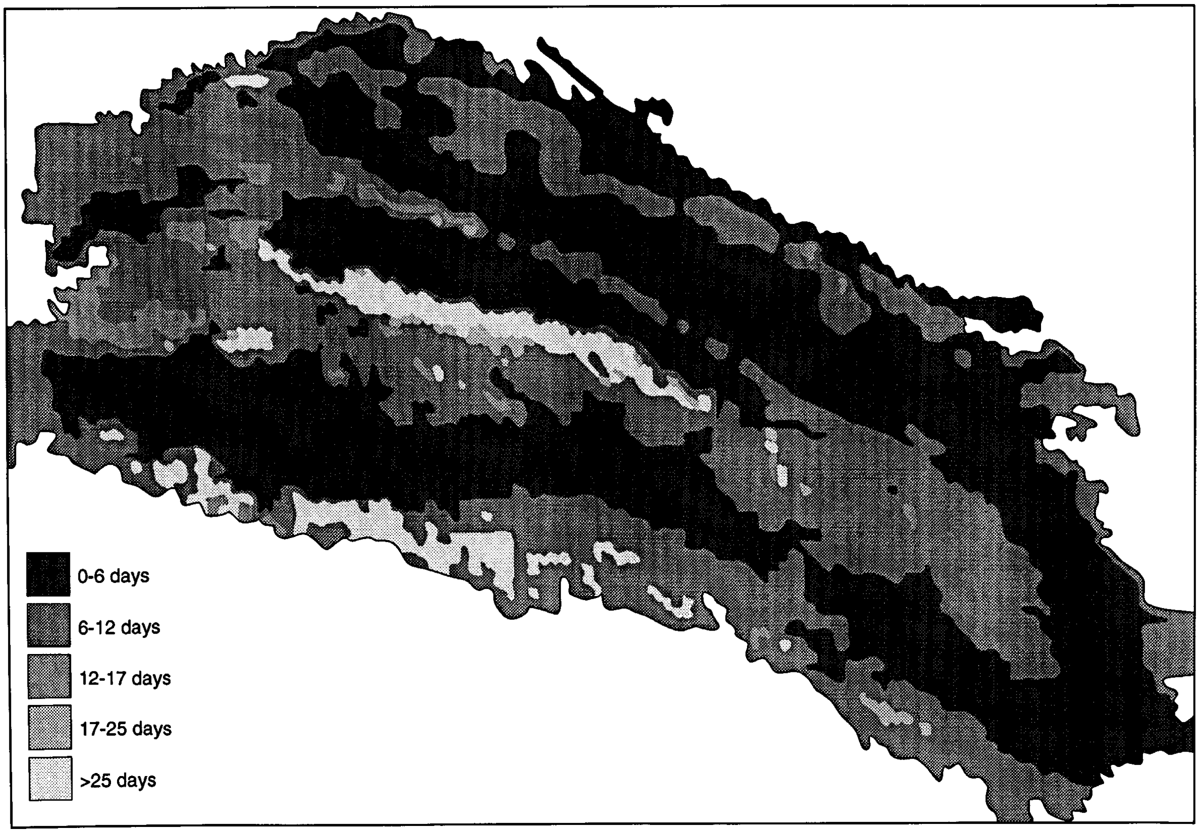

Figure 3. A plot of landform age 33 days after the first measurement of channel topography. Landform age at a point in the landscape is increased by the amount of time between each consecutive DTM only if there has been no erosion or no deposition in that time period.

and this is supported by both flume observations and numerical models of river channel change. Anderson and Calver (1981) undertook repeat simulations of flume channel patterns with mobile beds and found significant variation in aspects of pattern development among repeated experiments for the same conditions of discharge and initial slope. For a simple model of meander train evolution, Furbish (1991) found 'autocatalytic' behaviour in the governing equations, because any meander train configuration that arose during system evolution was itself an 'initial' condition for further evolution (cf. morphological conditioning above). Furbish argued that this challenges the conventional view (e.g. Ferguson, 1976) that the range of forms in a meander train reflects only perturbations (for example, by varied floodplain sedimentology) of a characteristic form, and that a range of diverse forms ought to develop independently of, but in addition to, random influences. As implied by Phillips (1992), it is impossible to find a particular configuration that '. . . *serves as an asymptotically stable, evolutionary state for individual bends* . . .' (Furbish, 1991, p. 1588).

Similar evidence is provided by a simplified computer model of braided river behaviour, based upon a spatially distributed, two-dimensional routing model for discharge and sediment (Murray and Paola, 1994). Water is routed through the model according to bed slope, which drives sediment transport by simple rules. This model reproduces many of the phenomena observed in real braided streams, with the overall channel pattern remaining statistically stable. However, the model never reaches a steady state, exhibiting apparently unpredictable changes in channel configuration indefinitely. Despite producing a *statistically* stable morphology (as with meandering systems), the system dynamics are inherently unstable and are driven by a continually changing morphology. Such a statistically stable morphology may represent some form of 'attractor', maintained for some significant time until a threshold is passed, or a bifurcation occurs, after which the system moves into a new statistically stable state. Huggett (1988) notes that such a bifurcation may result from either internal or external processes. For instance, net degradation could eventually reduce bed-slope

sufficiently that eventually a critical point on the system trajectory is reached where the system crosses the braided–meandered threshold into the meandering domain (an internal bifurcation). Alternatively, a reduction in discharge could also result in a transition from a braided to a meandering state (an external bifurcation). Again, short time-scales and small space-scale processes matter, both because small changes in system trajectory may have major effects upon long-term system evolution, if the conditions are right for those small changes to become amplified through positive feedback, and because it may only require a small change in system trajectory for a threshold to be passed and a bifurcation to occur.

Paola (1996) has argued that turbulence may provide a useful metaphor for braiding, since both are characterized by a hierarchy of scales (of eddies in turbulence and bars in braiding); both exhibit fractal behaviour; and in both, interactions between structures produce important events (ejections and sweeps in turbulence; confluences in braiding) that contribute disproportionately to transport (of momentum in turbulence, of sediment in braiding). In turbulence, there is a clear link between scales (the energy cascade), but Paola argues that such cross-scale links do not exist in the case of braiding. The evidence outlined in this paper, however, suggests that cross-scale coupling does occur. Just as recent turbulence research has suggested that anisotropic turbulence may be responsible for the formation of larger-scale flow structures in certain situations (e.g. Nezu *et al*., 1993), so short time-scale and small space-scale processes of bar formation and reworking result in longer time-scale and larger space-scale effects. Combined with the observations of morphological conditioning described above, it may remain the case that the cumulative effect of small time- and space-scale processes on system evolution cannot be adequately represented by average parameters, as the interaction between boundary conditions and processes at shorter time-scales and smaller space-scales results in system evolution in a manner that is different to that suggested by average parameters. This does not preclude the existence of an average state, and even in non-linear systems such states certainly exist. However, it does suggest that shorter time-scale and smaller space-scale processes are central to understanding movements between states. As in turbulence, there are critical cross-scale links, and the ‘whole’ of a river channel is more than the sum of its parts.

CONCLUSION

This paper has endeavoured to use a site-specific case study to identify some of the issues concerning links between short-term process studies and longer-term landform evolution. Most importantly, it has argued that the traditional view – that different scales of form and process are causally independent of each other – cannot be sustained, as short time-scale and small space-scale processes influence processes over longer time-scales and larger space-scales.

The results presented here are based upon intensive study of a specific river in a particular catchment. This may lead to questions about ‘representativeness’. Furthermore, the argument that the effect of a particular discharge depends not only on its interaction with sediment supply but also on existing channel morphology implies that every river channel will appear to be different, with a unique morphological configuration, and will also change in a unique manner. This demands close consideration of the nature of the generalization to be employed in studies of this kind. Ashmore (1991) has suggested that it is possible to identify particular styles of channel change in braided river systems, and that it may even be possible to make statements as to the frequency with which particular types of channel change occur. However, knowing these frequencies does not itself assist in determining which style of channel change will occur in a given instance. The field data presented here have also allowed the identification of different styles of channel change, but it follows from the above discussion that general statements about frequency of occurrence cannot be divorced from consideration of the specific context of a particular system. The context (that is, the interaction of a particular discharge and sediment supply event with a particular morphology) will determine the exact nature of system response. This observation emphasizes the challenge of making generalizations on the basis of a case study because empirical observations will contain information that reflects the channel which is studied. However, it may be possible to generalize theoretically about the processes of channel change that involve interaction of discharge and sediment supply processes, conditioned by channel boundary conditions (topography, sedimentology, vegetation). The difficulty of making observational generalizations on the basis of a case study should not be viewed as a

methodological impediment, but rather as a case for grounding research in those configurational contexts that are responsible for the nature of channel change. To remove such a site-specific context is to remove the very individuality of river channel behaviour, and to produce an artificial impression of order and rationality.

It is therefore useful to compare intensive field-study approaches with the study of channel change by alternative methods. Selection of a particular field-site results in the establishment of a specific set of boundary conditions. As such, this is no different from either a laboratory flume study or a numerical modelling approach, each of which involve some form of experimental closure (e.g. the choice of grain-size distribution and sediment feed rate in a laboratory study, or the way a particular set of processes is represented mathematically and parameterized in a numerical model). The observations that are made must be interpreted in the light of the context in which the analysis is then situated. In laboratory flumes, the ability of the user to control parameters such as grain size and channel shape means that the definition of boundary conditions is relatively easy. In the field, this is less often the case, but this is what is needed in order that generalization can occur rationally (Richards, 1996). Furthermore, rather than seeing these alternative methods as mutually exclusive, it is important that the fluvial geomorphologist emphasizes their complementarity. Laboratory experimentation and numerical modelling may allow greater control over the initial conditions within which immanent processes operate. However, in the absence of contextualization using field measurement, they will fail to recognize the crucial importance of configuration (e.g. morphological conditioning) in determining the behaviour of river systems, and the resemblance of their predictions to reality remains uncertain.

The recognition that short time-scale and small space-scale processes have implications for longer-term behaviour raises new challenges for the description and explanation of fluvial systems. Research has shown that it is possible to move from descriptions of short time-scale and small space-scale processes to the explanation of larger systems (e.g. Clifford, 1993), whilst the concurrent growth of non-linear systems thinking in other areas of the natural sciences (for example, ecology and atmospheric science) has shown that explanation using such concepts is both feasible and applicable (Pahl-Wostl, 1992; Palmer, 1993). Application of non-linear thinking in fluvial geomorphology has the potential to provide a new means of exploring links between form and process, without necessarily requiring *a priori* assumptions about which forms and processes are deemed irrelevant for a particular scale of enquiry. However, the identification of non-linear behaviour within fluvial systems is difficult (Montgomery, 1993), and the full implications of non-linear thinking for geomorphological understanding have yet to be assessed. If fluvial systems behave in a non-linear manner, the problem of identifying system response from observational records will be compounded. The difficulty of recognizing equilibrium states, which are essentially attractors, is well known. Identifying critical bifurcations during system evolution requires continual observation of a kind that is not common in process studies, where a search for the immanent, combined with a failure of recognize configurational aspects of system behaviour, has resulted in the formulation of statistical regularities whose relationship with system dynamics is weak. The continual observation of dynamic systems, whether in the field, the flume or the computer, takes on new importance in this respect. Similarly, it is increasingly important that the geomorphologist endeavours to consider links between the wealth of ‘traditional’ conceptual ideas of landform behaviour (e.g. Brunsden and Thornes, 1979) and new ideas of non-linear response. Non-linear thinking is not a significant conceptual departure from many of these (e.g. the importance of thresholds in landform evolution), but it does begin to challenge some of the methodological premises within which fluvial geomorphologists operate. The greatest challenge remains to understand the way in which short time-scale and small space-scale processes operate to result in long time-scale and large space-scale behaviour.

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